OPTIMAL SYNTHESIS OF OIL PALM ECO-INDUSTRIAL TOWN

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DEDICATION

To my dearest family:

Whose love has nourished and sustained me always.

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This thesis would not have been possible without the guidance, assistance and strength from Allah.

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ABSTRACT

The oil palm industry plays significant roles in developing Malaysia's economy, society and environment. Current oil palm industry practices produce millions of tons of oil palm biomass as bio-waste at plantations and mills. Untreated biomass waste leads to environmental problems such as waterways contamination and carbon dioxide emission (CO_2). Biomass waste produced reached 150 million tons in 2014, which comprised of decanter cake, boiler ash, empty fruit bunch, palm oil mill effluent, oil palm frond, and oil palm trunk. An oil palm eco-industrial town (EIT) was proposed as a new oil palm industry model to balance both economic and environmental needs by integrating oil palm based industries and community. The main objective of this study was to synthesise oil palm based industries for oil palm EIT by using structural optimisation. In order to achieve the goal, four sub-objectives were identified: (1) to develop a model that can determine the products and biomass-pathways that will give maximum profit to the oil palm EIT, (2) to develop a model that can decide the profitable products and biomass-pathway that will give maximum profit to the oil palm EIT while minimising impacts of CO_2 emissions to the environment, (3) to develop a model that is able to do spatial planning of centralised biomass facility, as well as location for spatial development of oil palm EIT, and (4) to develop a multi-period model that can decide the most profitable industries in oil palm EIT for the next 10 year period, taking into consideration the biomass yield based on age of the palm oil tree. A case study of Johor was applied in this research. The developed models were optimised by using General Algebraic Modelling System (GAMS) software as an optimisation tool. The developed models verified that the community and oil palm based industries can be integrated via oil palm EIT concept. The developed model named as the Economic Optimisation Model (EOM) found that the maximum profit that can be achieved by oil palm EIT was USD 67.27 million. The Green Economic Optimisation Model (GEOM) verified that the oil palm EIT can meet both economic and environmental needs with 0.96 degree of satisfaction, optimal profit of USD 65.50 million and total CO_2 emission of 464,210 kg-CO_2-eq. The oil palm EIT can achieve maximum profits of USD 163.37 million via decentralised system in cases where there are multi-site oil palm EITs, as demonstrated by the Multi-site Optimisation Model (MSOM). Multi-period Optimisation Model (MPOM) demonstrated the most profitable industrial elements to be developed for year 2016 to 2025. It was found that the maximum profit can be achieved by oil palm EIT for the 10 year period was USD 903.07 million. The oil palm EIT can be promoted as a green economic development model powered by oil palm biomass.

ABSTRAK

Industri kelapa sawit memainkan peranan penting dalam membangunkan ekonomi, masyarakat, dan alam sekitar Malaysia. Namun, amalan industri kelapa sawit semasa menghasilkan jutaan tan biojisim kelapa sawit sebagai bahan buangan di ladang dan kilang kelapa sawit. Bahan buangan biojisim yang tidak dirawat dengan baik mengundang masalah alam sekitar seperti pencemaran saliran dan pembebasan karbon dioksida (CO_2). Bahan buangan biojisim yang dijana mencecah 150 juta tan pada tahun 2014 termasuk serat, abu dandang, tandan sawit kosong, efluen kilang sawit, tandan dahan sawit, dan batang pokok sawit. Sebuah bandar eko industry (EIT) kelapa sawit dicadangkan sebagai model industri kelapa sawit baru untuk mengimbangi ekonomi dan alam sekitar dengan menggabungkan industri berasaskan kelapa sawit dengan komuniti. Objektif utama kajian ini adalah untuk mensintesis industri berasaskan kelapa sawit untuk EIT kelapa sawit dengan menggunakan kaedah pengoptimuman berstruktur. Bagi mencapai tujuan tersebut, empat sub-objektif dikenalpasti: (1) untuk membangunkan model yang boleh menentukan produk dan laluan biojisim yang dapat memberi keuntungan maksimum kepada EIT kelapa sawit, (2) untuk membangunkan model yang dapat menentukan produk dan laluan biojisim yang dapat memberikan keuntungan yang maksimum disamping meminimumkan pembebasan CO_2 ke alam sekitar, (3) untuk membangunkan model yang dapat merancang ruangan untuk pemusatan biojisim serta lokasi pembinaan EIT kelapa sawit, dan (4) untuk membangunkan model pelbagai-waktu yang dapat menentukan industri kelapa sawit yang menguntungkan bagi EIT kelapa sawit untuk tempoh 10 tahun akan datang dengan mempertimbangkan pengeluaran biojisim berdasarkan usia pokok kelapa sawit. Model-model yang dibangunkan dioptimumkan dengan menggunakan perisian Sistem Pemodelan Algebra Umum (GAMS) sebagai alat pengoptimuman. Model yang dibangunkan mengesahkan bahawa komuniti dan industri boleh digabungkan melalui EIT kelapa sawit. Model yang dibangunkan bernama Model Pengoptimuman Ekonomi (EOM) menunjukkan keuntungan maksimum yang boleh dijana oleh EIT adalah sebanyak USD 67.27 juta. Model Pengoptimuman Ekonomi Hijau (GEOM) pula mengesahkan bahawa EIT kelapa sawit boleh mencapai keseimbangan ekonomi dan alam sekitar dengan darjah kepuasan sebanyak 0.96, keuntungan optimum USD 65.50 juta dan jumlah pembebasan CO_2 adalah sebanyak 464,210 kg-CO_2-setara. Dalam kes wujudnya beberapa lokasi EIT kelapa sawit, keuntungan maksimum yang boleh dijana oleh EIT kelapa sawit adalah sebanyak USD 163.37 juta, melalui sistem nyahpusat sebagaimana ditunjukkan oleh Model Pengoptimuman Pelbagai-kawasan (MSOM). Model Pengoptimuman Pelbagai-waktu (MPOM) menunjukkan elemen industri yang paling menguntungkan bagi tahun 2016 hinga 2025. Keuntungan maksimum yang boleh dicapai oleh EIT bagi tempoh 10 tahun akan datang adalah USD 903.07 juta. EIT kelapa sawit boleh diperkenalkan sebagai model pembangunan ekonomi hijau berasaskan biojisim kelapa sawit.

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LIST OF ABBREVIATIONS

EFB	-	Empty fruit bunch
FFB	-	Fresh fruit bunch
EIT	-	Eco-industrial town
CPO	-	Crude palm oil
PK	-	Palm kernel
GAMS	-	Generalised Algebraic Modelling System
LP	-	Linear programming
MILP	-	Mixed integer linear programming
MINLP	-	Mixed integer nonlinear programming
MF	-	Mesocarp fibre
NLP	-	Nonlinear programming
PSE	-	Process systems engineering
POME	-	Palm oil mill effluents
USD	-	United States Dollar
OPF	-	Oil palm frond
OPT	-	Oil palm trunk

LIST OF SYMBOLS

RES_a	-	Amount of available external resource *a* per year (unit/y)
$CPCOST_r$	-	Amount of capital and maintenance cost of industry *r* per year (USD/y)
$EXPR_a$	-	Market prices of external resource *a* per unit material (USD/y)
$INPR_n$	-	Market price of internal resource *n* per unit material (USD/unit)
$TRCOST_l$	-	Treatment cost for internal resource (waste) *l* per unit material (USD/unit)
$CNVS_{rn}$	-	Conversion factor of industry *r* to produce internal resource *n*
$DEMUTY_f$	-	Demand of utility *f* for one ton processing main material at industry *r* (t/y or kW/y)
$ENVCO2_z$	-	Amount of CO_2 emission per unit material (kg-CO_2-eq/unit)
$EITPROFIT$	-	Total revenue of oil palm EIT per year (USD/y)
$PROFIT_r$	-	Revenue of industry *r* per year (USD/y)
$SALES_r$	-	Revenue of sales at industry *r* per year (USD/y)
$UTYCOST_r$	-	Expenses for utility at industry *r* per year (USD/y)
$CAPCOST_r$	-	Expenses for capital and maintenance cost at industry *r* per year (USD/y)
$MATCOST_r$	-	Expenses for feed material at industry *r* per year

		(USD/y)
$TREATCOST_p$	-	Expenses for waste treatment via conventional method per year (USD/y)
$EXMAT_{ir}$	-	Amount of external material *i* sent to industry *r* per year(t/y)
$EXUTY_{fr}$	-	Amount of external utility *f* sent to industry *r* per year (t/y)
$RMAT_r$	-	Amount of main material at industry r per year (t/y)
$PPRO_{rm}$	-	Amount of product *m* produced from industry *r* per year (t/y)
PRO_m	-	Amount of available product *m* produced in EIT per year (t/y)
$PROUSE_{mr}$	-	Amount of product *m* reuse by industry *r* per year (t/y)
$PROSALE_{ms}$	-	Amount of product *m* sent to market *s* per year (t/y)
$PBIO_{rl}$	-	Amount of biomass *l* produced from industry *r* per year (t/y)
BIO_l	-	Amount of available biomass *l* generated in EIT per year (t/y)
$BIOUSE_{lr}$	-	Amount of biomass *l* reuse by industry *r* per year (t/y)
$WASTE_{lp}$	-	Amount of biomass *l* sent to treatment facility *p* per year (t/y)
$PUTY_{ru}$	-	Amount of utility *u* produced from industry *r* per year (t/y or kW/y)
UTY_u	-	Amount of available utility *u* produced in EIT per year (t/y or kW/y)
$UTYUSE_{ur}$	-	Amount of utility *u* reuse by industry *r* per year (t/y or kW/y)

$UTYSALE_{us}$	-	Amount of utility *u* sent to market *s* per year (t/y or kW/y)
AIRCONT	-	Total amount of CO_2 emission per year ($kgCO_2$-eq/y)
λ	-	Degree of satisfaction
RES_{av}	-	Amount of available external resource *a* at *v* location (unit/y)
$CPCOST_{tv}$	-	Amount of capital and maintenance cost of industry *r* at *v* location (USD/y)
$EXPR_{va}$	-	Market price of external resource *a* per unit material at *v* location (USD/y)
$INPR_{vn}$	-	Market price of internal resource *n* per unit material at *v* location (USD/unit)
$TRCOST_{vl}$	-	Treatment cost for internal by-product *l* per unit material at *v* location (USD/unit)
$CNVv_{trvn}$	-	Conversion factor of industry *r* at v location to produce internal resource *n* at *v* location
$DEMUTY_{vrvf}$	-	Demand factor of utility *f* during *t* year at industry *r* during *t* year
$SPEX_{ar}$	-	External resource indicator to allow for the intake of external resource
		1 if external resource a is feed to industry r
		0 otherwise
$SPIN_{nr}$	-	Internal resource indicator to allow for the intake of external resource
		1 if internal resource n is feed to industry r
		0 otherwise
$DISTANCE_{ir}$	-	Travel distance of external resource *i* to industry *r* (km)

EITPROFIT	-	Total revenue of oil palm EIT per year (USD/y)
SALES	-	Total sales of oil palm EIT per year (USD/y)
UTYCOST	-	Total expenses for utility per year (USD/y)
CAPCOST	-	Total expenses for capital investment per year (USD/y)
MATCOST	-	Total expenses for feed material per year (USD/y)
TREATCOST	-	Total expenses for waste treatment per year (USD/y)
$EXMAT_{vivr}$	-	Amount of external material *i* sent from location *v* to industry *r* at location *v* per year (unit/y)
$EXUTY_{vfvr}$	-	Amount of external utility *f* sent from location *v* to industry *r* at location *v* per year (t/y or kW/y)
$RMAT_{vr}$	-	Amount of main material at industry *r* at location *v* per year (t/y)
$PPRO_{vrvm}$	-	Amount of product *m* at location *v* produced from industry *r* from location *v* per year (t/y)
PRO_{vm}	-	Amount of available product m produced at location *v* per year (t/y)
$PROUSE_{vmvr}$	-	Amount of product *m* from location *v* reuse by industry *r* at location *v* per year (t/y)
$PROSALE_{vms}$	-	Amount of product *m* from location *v* sent to market *s* per year (t/y)
$PBIO_{vrvl}$	-	Amount of biomass *l* at location *v* produced from industry *r* from location *v* per year (t/y)
BIO_{vl}	-	Amount of available biomass *l* generated at location *v* per year (t/y)
$BIOUSE_{vlvr}$	-	Amount of biomass *l* from location *v* reuse by industry *y* at location *v* per year (t/y)
$WASTE_{vlp}$	-	Amount of biomass *l* from location *v* sent to

		treatment facility p per year (t/y)
$PUTY_{vrvu}$	-	Amount of utility n at location v produced from industry y from location v per year (t/y or kW/y)
UTY_{vu}	-	Amount of available utility u produced at location v per year (t/y or kW/y)
$UTYUSE_{vrvu}$	-	Amount of utility u from location v reuse by industry y at location v per year (t/y or kW/y)
$UTYSALE_{vrs}$	-	Amount of utility u from location v sent to market s per year (t/y or kW/y)
YA		Selection for decentralised system
	-	1 if decentralised system is selected
		0 otherwise
YB		Selection for centralised system
	-	1 if centralised system is selected
		0 otherwise
XVB_{vb}		Selection for location of centralised system
	-	1 if location vb is selected
		0 otherwise
RES_{ta}	-	Amount of available external resource a during t year (t/y)
$CPCOST_{tr}$	-	Amount of capital and maintenance cost of industry r during t year (USD/y)
$EXPR_{ta}$	-	Market price of external resource a per unit material during t year (USD/y)
$INPR_{tn}$	-	Market price of internal resource n per unit material during t year (USD/y)
$TRCOST_{tl}$	-	Treatment cost for internal by-product l per unit material during t year (USD/y)

$CNVS_{trtn}$	-	Conversion factor of industry *r* during *t* year to produce internal resource *n* during *t* year
$DEMUTY_{trtf}$	-	Demand factor of utility *f* during *t* year at industry *r* during *t* year
$SPEX_{ar}$	-	External resource indicator to allow for the intake of external resource
		1 if external resource *a* is feed to industry *r*
		0 otherwise
$SPIN_{nr}$	-	Internal resource indicator to allow for the intake of external resource
		1 if internal resource *n* is feed to industry *r*
		0 otherwise
EITPROFIT	-	Total revenue of oil palm EIT for 10 years (USD)
SALES	-	Total sales of oil palm EIT for 10 years (USD)
UTYCOST	-	Total expenses for utility for 10 years (USD)
CAPCOST	-	Total expenses for capital investment and maintenance cost for 10 years (USD)
MATCOST	-	Total expenses for feed material for 10 years (USD)
TREATCOST	-	Total expenses for waste treatment for 10 year (USD)
$EXMAT_{titr}$	-	Amount of external material *i* during *t* year sent to industry *r* during *t* year (t/y)
$EXUTY_{tftr}$	-	Amount of external utility *f* during *t* year sent to industry *r* during *t* year (t/y)
$RMAT_{tr}$	-	Amount of main material at industry *r* during *t* year (t/y)
$PPRO_{trtm}$	-	Amount of product *m* produced during *t* year from industry *r* during *t* year (t/y)
PRO_{tm}	-	Amount of available product m produced during *t*

		year (t/y)
$PROUSE_{tmtr}$	-	Amount of product *m* during *t* year reuse by industry *r* during *t* year (t/y)
$PROSALE_{tms}$	-	Amount of product *m* during *t* year sent to market *s* (t/y)
$EXPRO_{tmtm}$	-	Amount of product *m* during *t* year sent to product *m* at *t+1* year (t/y)
$PBIO_{trtl}$	-	Amount of by-product *l* produced during *t* year from industry *r* during *t* year (t/y)
BIO_{tl}	-	Amount of available by-product *l* generated during *t* year (t/y)
$BIOUSE_{tltr}$	-	Amount of by-product *l* during *t* year reuse by industry *r* during *t* year (t/y)
$WASTE_{tlp}$	-	Amount of by-product *l* during *t* year sent to treatment facility *p* (t/y)
$PUTY_{trtu}$	-	Amount of utility *u* during *t* year produced from industry *r* during *t* year (t/y or kW/y)
UTY_{tu}	-	Amount of available utility *u* produced during *t* year (t/y or kW/y)
$UTYUSE_{trtu}$	-	Amount of utility *u* during *t* year reuse by industry *r* during *t* year (t/y or kW/y)
$UTYSALE_{trs}$	-	Amount of utility *u* during *t* year sent to market *s* (t/y or kW/y)
XVB_{vb}		Selection for industry in EIT
	-	1 if industry *vb* is selected
		0 otherwise

Greek Letters

$\sum$	-	Summation
$\forall$	-	All belong to

Subscripts

a	-	Index for types of industrial input
i(a)	-	Index for types of input material
f(a)	-	Index for types of input utility
r	-	Index for types of industrial and community
n	-	Index for types of industrial output
m(n)	-	Index for types of main-products
u(n)	-	Index for types of utility
s	-	Market
p	-	Treatment facility
z	-	Index for CO_2 emission
v	-	Index for location
t	-	Index for period

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CHAPTER 1

INTRODUCTION

1.1 Introduction

Palm oil is one of the most important edible oils in the world. Being one of the world's main palm oil producers, Malaysia plays a significant role toward sustainability in palm oil production. This chapter elaborates on research background, problem statement, research objectives and scope of work related to development of oil palm eco-industrial town model. Finally, this chapter highlights the contributions of this study towards the research and development of the oil palm industry.

1.2 Palm Oil Outlook

Palm oil is the highest oilseed's producer in the world compared to other oilseed. Based on total production of oilseed in the past four years as shown in Figure 1.1, palm oil has the highest production with 291.53 million tonne (Mt), followed by soybean 231.76 Mt, rapeseed 128.8 Mt, sunflowerseed 72.68 Mt, palm kernel 34.36 Mt, peanut 27.43 Mt, cottonseed 25.18 Mt, coconut 17.23 Mt and the lowest, olive with 14.32 Mt. Oilseed production from oil palm tree (palm oil and palm kernel) represented 37 - 39% of total annual oilseed production between 2012 to 2016. The palm oil is the world's main consumption for edible oil, which represents 35% of total edible oil consumption, followed by soybean 29%, rapeseed 15%, sunflower seed 8%, palm kernel 4%, peanut 3% and other oilseed oil 2%. Production and demand factors make palm oil the most profitable oilseed in the world. World's edible oil main consumption for palm oil, soybean, rapeseed seed,

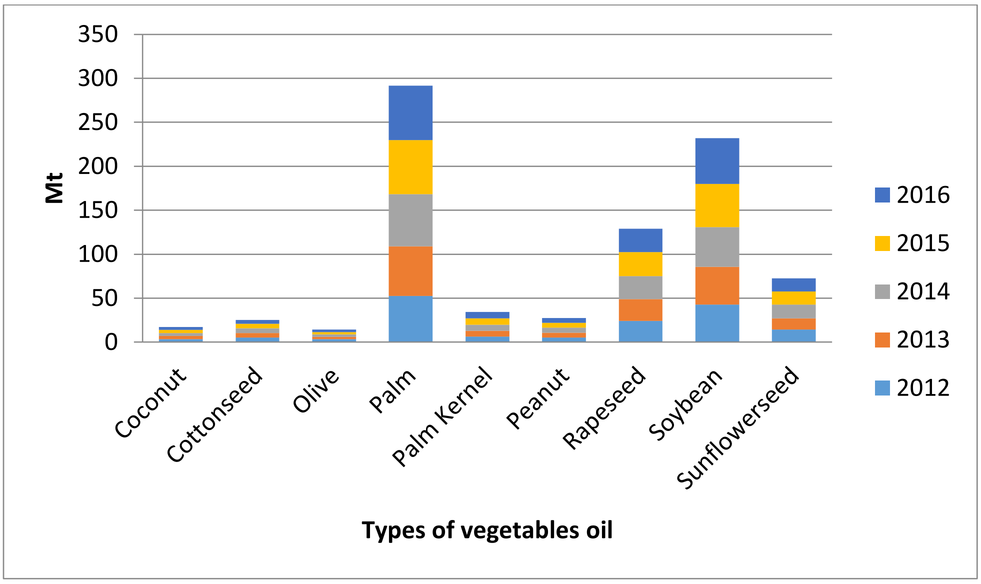

Figure 1.1 World edible oil production from 2012-2016 (USDA, 2016)

sunflower seed, palm kernel, peanut and other oilseed is shown by Figure 1.2 in the next page.

Oil palm has high productivity and efficiency compared to other oilseeds. This has been proven by the land use for oilseed cultivation; it was reported that oil palm cultivation used only 5.5 % of total cultivated land compared to the soybean that uses 40% of total cultivation land for oilseed. Sime Darby Plantation, (2014) reported that oil palm can produce about 8 t/ha of oil yearly or more than 10 times yield compared to other oilseed crops. Figure 1.3 in the next page shows world palm oil main producer in 2016. Indonesia was the world largest palm oil producer with 54%, followed by Malaysia with 31%, Thailand 4%, Columbia 2%, and lowest was Nigeria with 1%. Indonesia and Malaysia produces 85% of total world palm oil in 2016 with Malaysia contributing 31%. Being the second largest palm oil producer, Malaysia has planted about 5.64 Mha of oil palm tree, 17% of Malaysia's land size.

Oil palm is an important economic crop for Malaysia. This industry contributed about RM 41.26 billion to the country's revenue in 2016. Major importers for Malaysia's palm oil in 2016 are India (3.69 Mt), European Union (2.43 Mt), China (2.38 Mt), Pakistan (0.73), USA (0.7 Mt), Philippines (0.65 Mt), and Vietnam (0.58 Mt). Total amount of palm oil exported to these seven countries accounted for 64% of total Malaysia's palm oil export. Most of the exported palm oil, either in the form of crude palm oil or palm kernel oil, is mainly used in food and non-food industries as cooking oil and feedstock for processing activities such as animal feeds mix.

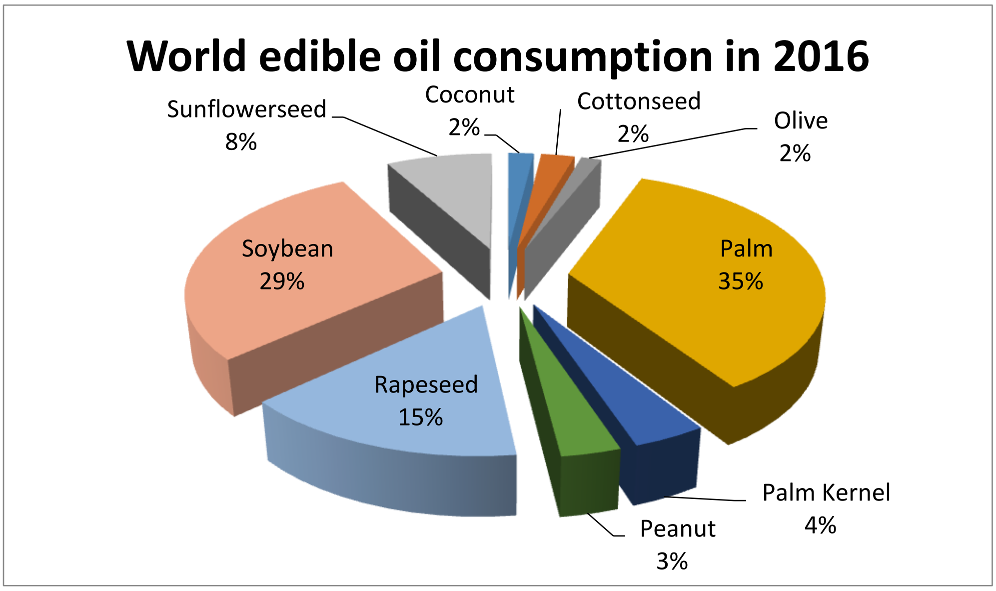

Figure 1.2 World edible oil consumption in 2016 (USDA, 2016)

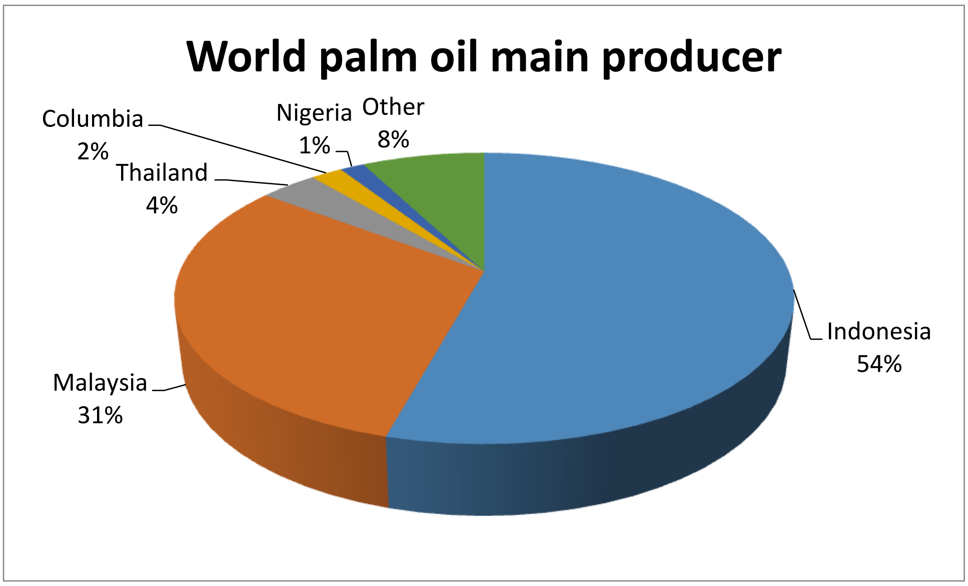

Figure 1.3 World oil palm producer in 2016 (USDA, 2016)

1.3 Background of Research

Oil palm is one of the most important crops in Malaysia in the aspect of the economic, environmental and social benefits. Malaysia has established more than 400 palm oil mills to extract oils from fresh fruit bunches (FFB) into crude palm oil (CPO) and palm kernel (PK) (MPOB, 2015b). However, oil palm industry also generates large amount of unused oil palm biomass. It is estimated that in 2014, about 157 million tonne (Mt) of oil palm biomass were produced by the plantations and palm oil mills in Malaysia. About 43% of the oil palm biomasses are at the plantation, which includes oil palm frond (OPF) and oil palm trunk (OPT). The remaining 57% of oil palm biomass are available at the palm oil mills, which includes empty fruit bunches (EFB), palm oil mill effluent (POME), oil palm shell (OPS), and mesocarp fibre (MF).

There have been many efforts of utilising oil palm biomass. Yoshizaki et al., (2013) investigated a new approach for utilising POME and EFB via integrated technology of biogas energy and compost production. Combustion of EFB, OPS and MF can generate at least 20 MW of electricity, as reported by Nasution et al. (2014). Chiew and Shimada (2013) studied the trend of utilising oil palm residue and the environmental performance of recycling technologies being used for fuel, fibre, and fertilizer in Malaysia. Unfortunately, not all oil palm biomass are being utilised optimally. Oil palm biomass such as EFB, OPT, OPF, OPS, MF and POME need to be transported to other processing mills in order to be processed into other oil palm based products. Factors such as technology, cost, and physical properties make this valuable biomass dumped at palm oil mills and plantations. This situation contributes negative impact to the environment, such as CO_2 emission and other GHG being released to the atmosphere. Extensive research is needed to find optimal palm oil biomass to energy conversion, with minimum waste generation and valuable by-products (Bazmi et al., 2011).

On the other hand, eco-industrial cluster (EIC) can effectively use biomass by converting them into other marketable product and bio-energy form. EIC employs industrial symbiosis approach to reduce energy usage, material consumption, waste generation and GHG emission. Generally, several industries will be clustered at the same location and cooperate with each other via the industrial symbiosis approach.

Note that waste output from one industry becomes the raw material input to another industry within the EIC. This helps the industry to generate additional income by selling waste and reduce cost for waste disposal. Besides that, transportation cost can be eliminated as the waste or materials are transported to nearby industries. In fact, this industrial model has been proven to play a vital role in developing countries such as Vietnam, India, Thailand and other countries, through GDP increment and social development. Even as EIC benefits the community via local economic generation and job opportunity, the community itself are not directly involved with material or energy sharing in EIC. Towards sustainability, the community should be integrated with the industries in the EIC model. The concept of industrial symbiosis as illustrated in Figure 1.4.

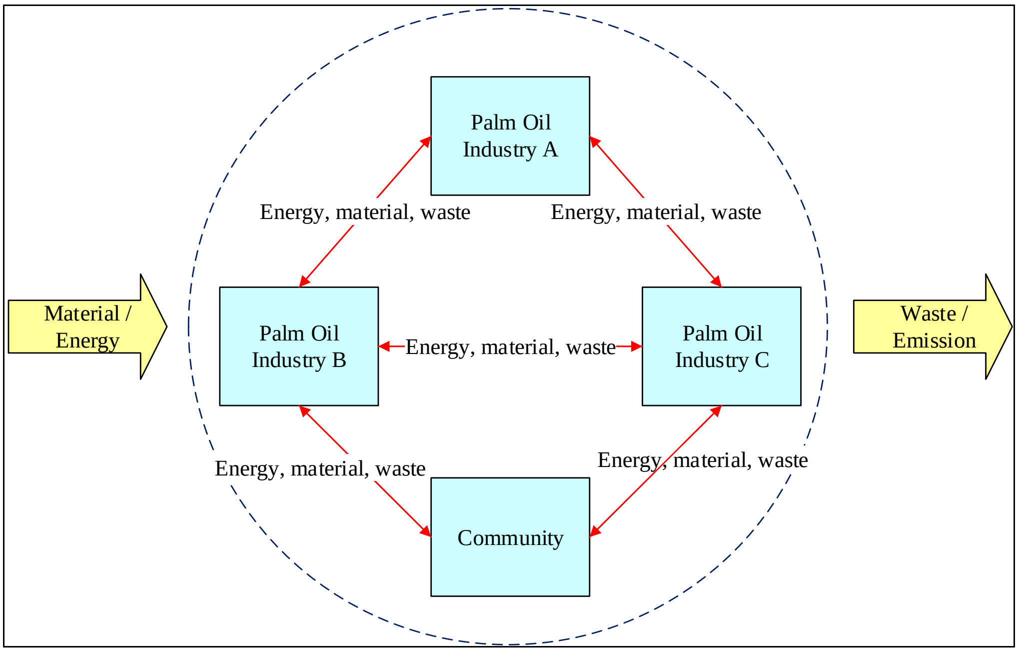

Figure 1.4 Schematic diagram of industrial symbiosis embedded in EIT

Oil palm industry in Malaysia has the potential to create oil palm eco-industrial town (EIT) by utilising availability of oil palm biomass and employing eco-industrial cluster concept. The EIT integrates the industries and community via material and energy sharing in one location. Oil palm eco-industrial town (EIT) could contribute to the economy, environment and play a vital role in the green economic development for the local community. Among potential industries that could be incorporated in the EIT are bio-fertilizer industry, biogas industry, paper and pulp industry, oil palm plantation, crude palm oil mill, bio-fuel industry, and livestock industry. Aside from bringing positive impact to the economic value, these industrial activities also benefit the local community by providing job opportunities and developing the area continuously. Thus, oil palm based industries should evolve into EIT as a smart green economic development. The concept of EIT, eco-town and eco-industrial cluster is shown in Figure 1.5.

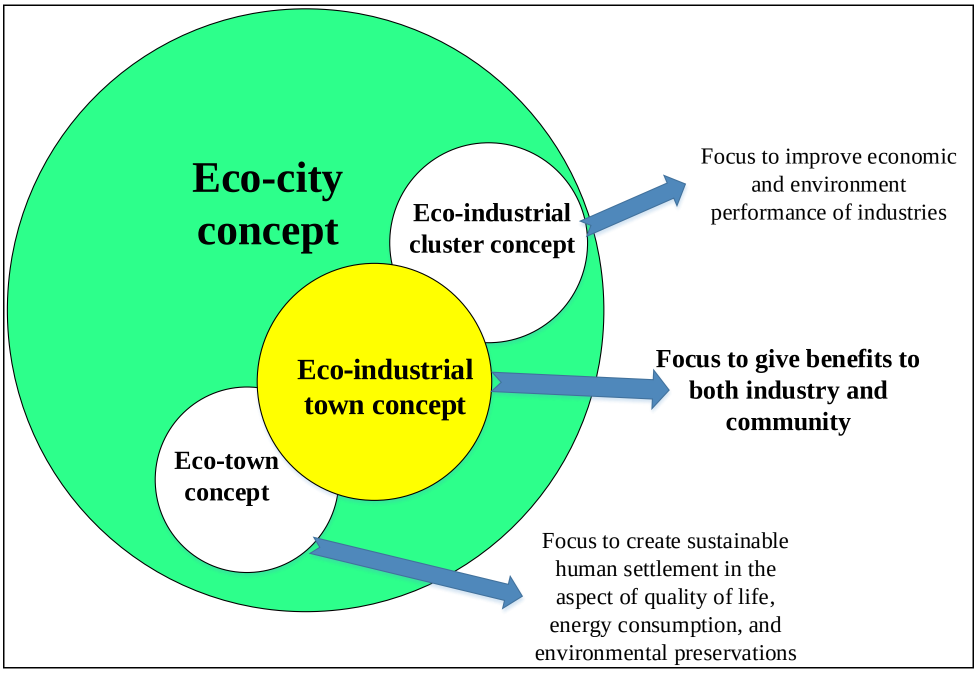

Figure 1.5 Eco-town, eco-industry cluster and eco-industrial town concept

1.4 Problem Statement

Malaysia has a vast amount of oil palm biomass resources not being efficiently utilised. An estimated 90% of harvested oil palm plantation goes to waste, with only 10% to palm oil. In 2016, the industry generated around 83 million tonnes of biomass, with the volume expected to increase between 85 to 110 million dry tonnes by 2020. This quantity represents a sizeable opportunity to produce new wealth creation through production of value added bio-based products on an industrial scale. In 2015, the five companies - Genting Sdn Bhd, Kelas Wira Sdn Bhd, Bell Corp Sdn Bhd, Teck Guan Industries Sdn Bhd and Golden Elate Sdn Bhd formed biomass cluster. The cluster, led by the Malaysian government's Innovation Agency (Agensi Innovasi Malaysia, or AIM), aims to address gaps in the market between biomass owners and downstream users such as bio-based chemical refineries. Following are the gaps identified in the current oil palm industrial cluster in Malaysia:

1) Small scale of systematic planning of resources and demand, and the absence of centralised collection and processing system on a commercial scale has been an obstacle for the downstream bio-based industry. Hence, biomass resource and demand planning optimisation model is essential in providing sustainable supply of biomass to enhance the economy of downstream biomass industries.
2) Numerous researches on integration of biomass supply chain have been conducted. However, there are lack of studies on potential of biomass conversion to various value added products and spatial planning of biomass resources at a huge scale, resulting in underutilisation of biomass.
3) EIT concept is introduced in this study in order to systematically plan the biomass availability based on market demand and its downstream product; such as bio-energy generation, production of compost and bio fertilisers, manufacture of eco-products, as well as production of bio-based fuels and chemicals. Although there have been various EIT model implemented successfully in other countries such as Denmark, UK and China, the literature indicates the lack of integrated EIT model with spatial planning and community for long term planning. In this study, an

optimal network of biomass resource-to-downstream products can be developed through implementation of palm oil EIT concept. Therefore, sustainable economic and environmental benefits for palm oil EIT is expected with optimum utilisation of palm oil biomass at minimum cost, which leads to better planning and biomass management in the country.

The problem statement for this research is stated as follows:

Given a case study of current oil palm industry and its downstream industries in Malaysia, it is desirable to synthesize a local oil palm eco-industrial town which includes calculation of potential profit, assess impact of CO_2 emission, and plan for development of oil palm EIT using structural-based optimisation.

1.5 Research Questions

In order to design sustainable oil palm EIT, a few research questions must be addressed. The research questions of this study are as follows:

1) What are the potential bio-based products that can be produced by the oil palm EIT in order to maximise profitability?
2) What is the potential profit that can be achieved by the oil palm EIT while minimising the CO_2 emission to the environment?
3) Whether a decentralised or a centralised system is more cost effective for development of oil palm EIT, if there are a number of oil palm biomass resources (plantations and crude palm oil mills) in a single area?
4) What are the most profitable industries in the oil palm EIT for a 10 year period, if the oil palm EIT is developed gradually?

1.6 Research Objective

The main objective of this research is to develop a new systematic framework to synthesize a local oil palm eco-industrial town (EIT) using structural-based optimisation. The sub-objectives are as follow:

1) To develop and optimise a mathematical model that can determine the profitable products and biomass-pathways that will give maximum profit to the oil palm EIT.
2) To develop and optimise a mathematical model that can decide the profitable products and biomass-pathway that will give maximum profit to the oil palm EIT, while minimising the impacts of CO_2 emission to the environment.
3) To develop spatial planning optimisation model to centralise biomass facility for spatial development of oil palm EIT.
4) To develop multi-period optimisation model for development of oil palm EIT in a 10 year time horizon, taking into consideration biomass yield based on age of palm oil tree.

1.7 Scope of the Work

In order to achieve the intended research objectives, several scope of the study have been identified as follows:

1) Literature review on the current and the state-of-the-art scenario on:
    i. The oil palm biomass utilisation in oil palm based industry, including the processes, limitations and potential enhancement.
    ii. The process network, modelling, and optimisation in oil palm industrial cluster model.
2) Developing an optimisation model, namely *Economic Optimisation Model (EOM)* for oil palm EIT. The specific objectives are:
    i. Identifying potential oil palm based industries including their raw materials, utilities, process conversions, products and by products.
    ii. Developing a mathematical model that can identify material flow of oil palm biomass into oil palm based products in each industry in the oil palm EIT.
    iii. Optimising the developed model with aims to maximise the overall profit of oil palm EIT.

iv. Performing sensitivity analysis on case study to analyse and evaluate the economic and technical performances of the designed *EOM* model.

3) Developing an optimisation model, namely *Green Economic Optimisation Model (GEOM)* for oil palm EIT. The specific objectives are:

    i. Investigating impact of oil palm EIT operation on the CO_2 and other greenhouse gasses (GHG) emission.

    ii. Developing a mathematical model that can calculate impact of material flow and utilities in EIT to CO_2 and other GHG emission.

    iii. Optimising the developed model with aims to maximise overall profit of oil palm EIT while minimising impact of CO_2 emission to the environment.

    iv. Performing sensitivity analysis on case study to analyse and evaluate the economic, environment and technical performances of the designed *GEO* model.

4) Developing an optimisation model, namely *Multi-site Optimisation Model (MSOM)* for spatial development planning of oil palm EIT.

    i. Identifying location of crude palm oil mills, potential location for centralised system and transportation network in State of Johor.

    ii. Calculating the operational cost for decentralised system and centralised system including the capital and maintenance cost, and transportation cost.

    iii. Developing a mathematical model that decides the operational system for development of oil palm EIT at one area, whether to apply a decentralised or a centralised system.

    iv. Optimising the developed model with aims to maximise the overall profit of oil palm EIT.

    v. Performing sensitivity analysis on case study to analyse and evaluate the economic and technical performances of the designed *MSOM* model.

5) Developing an optimisation model, namely *Multi-period Optimisation Model (MPOM)* for gradual approach development planning of oil palm EIT.
    i. Investigating availability of oil palm biomass after 10 years of planting.
    ii. Studying demand for oil palm based products via policies and National Biomass Strategy 2020.
    iii. Developing a mathematical model that decides the time to develop each of the industries in oil palm EIT within the 10 year horizon.
    iv. Optimising the developed model with aims to maximise overall profit of oil palm EIT.
    v. Performing sensitivity analysis on case study to analyse and evaluate the economic and technical performances of the designed *MPOM* model.

1.8 Research Contributions

The key contributions of this work are summarised as follows:

1) A new optimisation model for maximising profitability of the oil palm EIT.
    - A generic linear programming model (LP) has been developed to identify biomass-pathway in the oil palm EIT.
    - Economic performances including profit, sales, material cost, utility cost, capital and maintenance cost for each industry in the oil palm EIT has been modelled.
    - The model considered the benefit of oil palm EIT to the community via electricity supply and waste utilisation.
2) A new optimisation model for green economic model of oil palm EIT.
    - The multi-objectives linear programming model has been developed to achieve both economic and environmental performances.

- The model is able to maximise total profit of oil palm EIT while minimising the impact of CO_2 emission to the environment.

3) A new optimisation model for spatial development planning of oil palm EIT.
   - A mixed integer linear programming (MILP) model that is capable of selecting operational system and location for spatial development planning of oil palm EIT.
   - ArcGIS is employed for spatial data and network analysis is conducted for biomass transportation in the developed model.
4) A new optimisation model for gradual development planning of oil palm EIT.
   - A mixed integer linear programing (MILP) model developed to identify the most profitable industries in the oil palm EIT for a 10 year time horizon.
   - The model is able to plan the development of oil palm EIT gradually for a 10 year time horizon.

Appendix A highlights all the publications and corresponding key contributions of this thesis towards the new body of knowledge in designing and planning of an oil palm EIT.

1.9 Organisation of the Thesis

This thesis consists of eight chapters. Chapter 1 gives an overview of the oil palm industry issues, problem background, problem statement, objectives and scope of the research which aims to develop a new systematic framework for an oil palm eco-industrial town by using the mathematical approach

In Chapter 2 of this thesis describes the fundamental theory and relevant literature related to the optimal synthesis of oil palm eco-industrial town. This chapter also describes the oil palm biomass scenario in Malaysia and reviews the utilisation of oil palm biomass globally. Moreover, this chapter reviews the eco industrial cluster concept that has been applied to different industries and the potential of oil palm eco industrial cluster. Next, this chapter reviews the state-of-the-art process systems engineering (PSE) approach applied to biomass based industry and community. At the end of Chapter 2 presents the state-of-the-art oil palm eco industrial town and highlights the specific research gaps for each review.

Chapter 3 presents the concept of oil palm EIT and generic methodology used in solving optimisation issues in developing an oil palm EIT. The concept of oil palm EIT integrates nine oil palm based industries and community at once location; including oil palm plantation, crude palm oil mill, bio-fertiliser mill, medium density fibre mill, biogas mill, paper mill, biodiesel mill, ruminant pellet mill, and livestock production of cows. This chapter also discusses the framework for development model of oil palm EIT and generic methodology that used in solving optimisation issues.

Chapter 4 present the *Economic Optimisation Model (EOM)* for maximising profitability of the oil palm EIT. In this chapter, a linear programming (LP) model is formulated to maximise economic performances of oil palm EIT by identifying the most profitable biomass route utilisation. Economic performances including profit, sales, material cost, utility cost, capital and maintenance cost for each industry in the oil palm EIT also expressed by the *EOM*.

Chapter 5 present the *Green Economic Optimisation Model (GEOM)* for maximising profitability, while minimising amount of CO_2 emission of oil palm EIT. In this chapter, a multi-objectives linear programming (LP) model is formulated to maximise economic performances of oil palm EIT by identifying the most profitable biomass route utilisation that will minimise the impact of CO_2 emission to the environment. Economic performances including profit, sales, material cost, utility cost, capital and maintenance cost for each industry in the oil palm EIT also expressed by the *GEOM*.

Chapter 6 present the *Multi-site Optimisation Model (MSOM)* for spatial development planning of oil palm EIT. In this chapter, a mixed-integer linear programming (MILP) model is formulated to maximise economic performances of oil palm EIT by selecting the most profitable operation system for development of oil palm EIT at one area, whether to apply a decentralised or a centralised system. The *MSOM* used spatial data included location of crude palm oil mills, potential location for centralised system and transportation network in State of Johor. The used of

ArcGIS as GIS tool for network analysis (biomass transportation) is also discussed in this chapter.

Chapter 7 present the *Multi-period Optimisation Model (MPOM)* for gradual approach development planning of oil palm EIT. In this chapter, a mixed-integer linear programming (MILP) model is formulated to maximise economic performances of oil palm EIT by deciding the most profitable industries in 10 years' time horizon for gradual development planning of oil palm EIT. The forecasted amounts of oil palm biomass and product demand for 2016-2025 are presented in this chapter.

Chapter 8 summarises the key contributions of this research, prior to the recommendations of possible future work. Figure 1.6 shows the flow and linkage of the chapters.

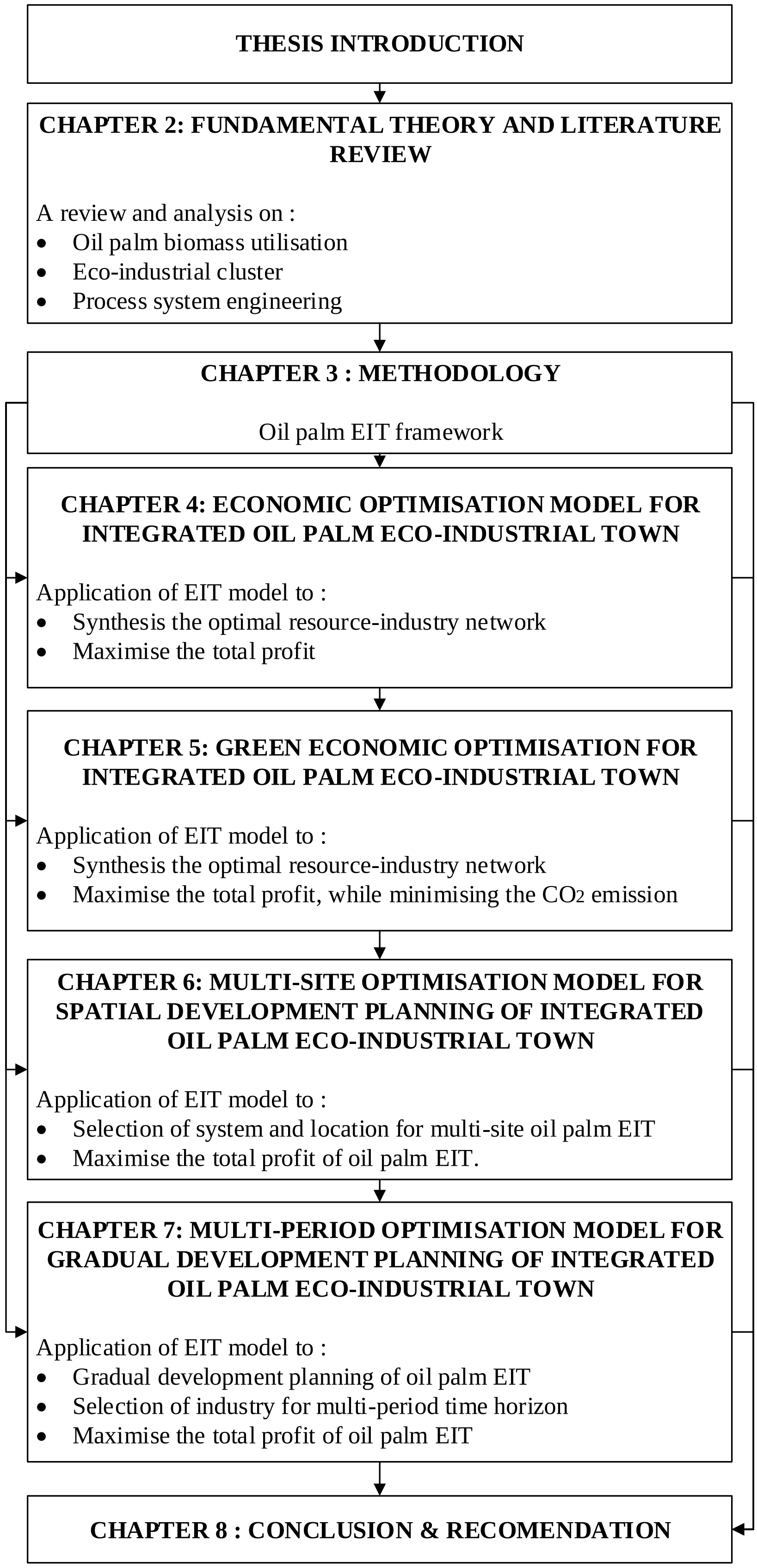

Figure 1.6 Flows diagram illustrating the conceptual link among the chapters

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